Semester Report – 2nd Semester

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PhD Thesis Title:
Measurements of Neutrino Charged-Current Interactions in Liquid Argon Using a Multi-GeV Neutrino Beam

1. Introduction

Neutrinos are fundamental, electrically neutral, and exceedingly light particles that primarily interact via the *weak interaction*. Their non-zero masses, confirmed by observations of neutrino oscillations at experiments such as Super-Kamiokande and the Sudbury Neutrino Observatory [1, 2], provide direct evidence of physics beyond the Standard Model. Understanding neutrinos' properties and interactions remains a major goal in modern particle physics.

The Deep Underground Neutrino Experiment (DUNE) aims to precisely measure neutrino oscillation parameters, investigate leptonic CP violation, and search for physics beyond the Standard Model. Its near detector (ND) complex will play a pivotal role in controlling systematic uncertainties related to neutrino flux prediction and neutrino-nucleus interaction for neutrino oscillation studies.

The DUNE near detector (ND) complex will consist of multiple detector technologies, including the planned ND-LAr (Near Detector Liquid Argon), a modular liquid-argon time projection chamber (LArTPC). The ND 2×2 is a smaller-scale technology demonstrator for the ND-LAr design. It consists of four liquid-argon time projection chamber (LArTPC) modules, each approximately $1\,\text{m} \times 1\,\text{m} \times 3\,\text{m}$ in size, arranged in a 2×2 array. The ND-2×2 demonstrator is constructed and operated on-axis in the NuMI (Neutrinos at the Main Injector) beamline at Fermilab, whereas the full ND-LAr detector will be located at the LBNF beamline in the future. The detector is currently not taking data due to a NuMI beamline shutdown at Fermilab. Current expectations are that data-taking may resume in late 2025, pending completion of NuMI beamline repairs. The **ND $\mathbf{2\times2}$** is the first DUNE detector receiving neutrino beam from the NuMI beamline, and it will provide high-statistics measurements of neutrino-argon interactions. Accurate flux predictions is essential for reducing key uncertainties, which include hadron production cross sections, neutrino interaction modeling, and beamline configuration uncertainties, in these measurements. To validate and improve the accuracy of neutrino flux predictions at the ND 2×2 location, we first simulate the expected NuMI on-axis neutrino flux and then refine this prediction by incorporating external hadron production data from the NA61/SHINE experiment. In particular, the dk2nu ntuples, which store detailed neutrino production information, and the PPFX (Package to Predict the Flux) framework [3], which reweights the simulated flux using external hadron-production data, form the foundation for this approach [4], [5].

Last semester, I set up all necessary simulation and analysis steps and successfully reproduced the NuMI on-axis flux prediction. Building upon that foundation, this semester I extended the analysis by performing a 100-universe PPFX run, where each "universe" corresponds to a distinct set of randomly varied input parameters within their uncertainties. This approach enabled the generation fractional-uncertainty histograms and component-wise systematic breakdowns through a modified `numi_flux` [1] wrapper originally developed by Dr. Nitish Nayak. These developments establish a robust baseline to support future flux predictions and systematic studies for the DUNE ND 2×2 detector.

2. Description of Research in the Current Semester

2.1 Dataset and Computing Environment

The analysis uses a set of 498 pre–re-weighted ROOT files originally produced for MicroBooNE—a detector located 468 m downstream of the NuMI target and slightly off-axis at Fermilab—and repositioned them to the NuMI on-axis location where the DUNE ND 2×2 detector is placed.[2] Each file contains a `dk2nu` flux ntuple with the NuMI medium-energy (ME) beam, which refers to a configuration of the NuMI beamline where 120 GeV protons strike a graphite target, producing a neutrino beam with energies peaked around 6 GeV. These files are suitable for this study because they reflect the NuMI beamline geometry and were simulated with Geant4.10.4 [6], aligning with modern setups used for flux predictions.

All large-scale data processing was performed on the DUNE collaboration's distributed computing infrastructure ("the grid"). This system allows many computational jobs to run in parallel, making it feasible to process large datasets.

2.2 Upgrading the `numi_flux` Wrapper

To evaluate uncertainties from different sources (such as pion and kaon production, or hadron interaction cross sections), I modified the `numi_flux` analysis script. Now, for each systematic effect considered in PPFX, a separate column (called a "branch" in ROOT terminology) is added to the output file. For example, weights representing uncertainty from pion production ("thin-target pion") and target attenuation are each stored in their own dedicated columns. This approach allows downstream analysis of the individual contributions to the total uncertainty, without repeating the entire data processing chain.

2.3 PPFX Uncertainty Propagation

PPFX handles uncertainty by employing a "many-universes" approach [7], where each universe varies input parameters influencing the flux according to a Gaussian distribution, with widths corresponding to the parameters' stated uncertainties, while preserving correlations between parameters. This method generates a large set of flux predictions, where each prediction corresponds to one possible way that all input parameters could vary within their uncertainties. Using an upgraded wrapper, I executed 100 different simulated scenarios (a 100-universe PPFX run) on the 498-file data set. This run reproduces the central-value NuMI on-axis flux (Fig. 1) and, for each energy bin E_j, produces universe weights w_{ij} that reflect the variations across the $N = 100$ universes.

The uncertainty on the predicted flux for each bin j is derived from the root-mean-square (RMS) variation of the weighted fluxes across the universes. The nominal flux Φ_j for bin j is the central weighted sum of events (e.g., $\sum wgt \cdot wgt_{j,\text{central}}$, where $wgt_{j,\text{central}}$ is the central weight like wgt_{ppfx}), and the universe-weighted flux for universe i is $wgt \cdot w_{ij}$, where w_{ij} is the universe-specific weight (e.g., an element of $wgt_{\text{ppfxunivs}}$). The RMS spread, σ_j, is then

[1] The `numi_flux` wrapper is a user-written script that simplifies running and analyzing PPFX reweighting for NuMI flux ntuples.

[2] Courtesy of Dr. Nitish Nayak.

computed as:

$$\sigma_j = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left((wgt \cdot w_{ij}) - \Phi_j\right)^2}$$

The fractional uncertainty for each bin is then:

$$\delta_j = \frac{\sigma_j}{\Phi_j}$$

This fractional uncertainty δ_j quantifies the relative spread of the universe variations around the central flux prediction, providing a measure of the systematic uncertainty due to PPFX reweighting.

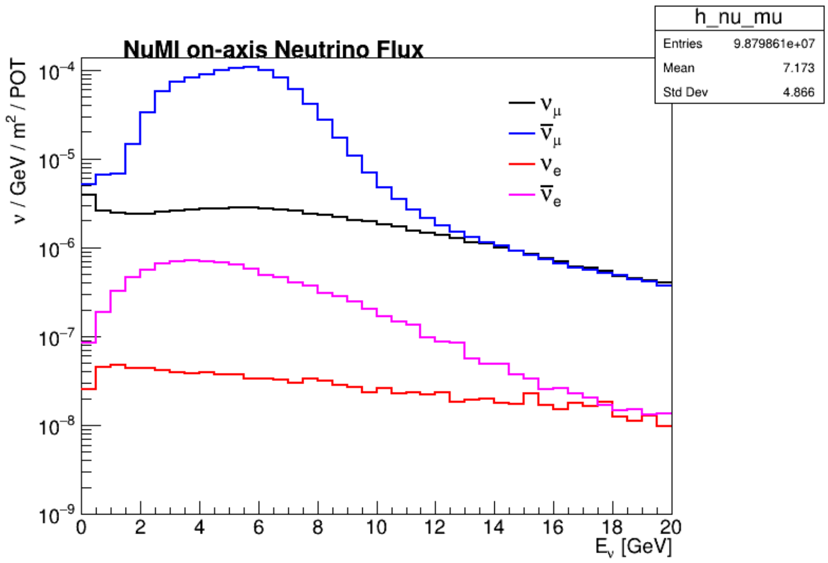

Figure 1: NuMI on-axis neutrino energy spectra at the ND 2×2 location. The dominant ν_μ flux peaks at approximately at 6 GeV.

2.4 Fractional-Uncertainty Breakdown

Figure 2 presents the fractional uncertainties of the PPFX-reweighted flux, with separate curves for the main systematic components that contribute to the total uncertainty. These components include thin-target pion and kaon production in p+C interactions (TT pC $\to \pi X$, TT pC $\to KX$), secondary nucleon production (TT pC $\to$ Nucleon$X$, TT nC $\to \pi X$, TT NucleonA), meson interaction cross sections (Meson Inc.), target attenuation, absorption, and other smaller effects grouped as "Others." The black curve represents the total PPFX uncertainty, which is computed from the RMS spread of the multisimulated scenarios and includes correlations between the different sources. This breakdown illustrates how individual systematic uncertainties, propagated through the simulated scenarios, contribute to the total uncertainty as quantified by the RMS method.

2.5 Summary and Outlook

This semester's activities—including improvements to the analysis tools, comprehensive uncertainty studies using multiple simulated scenarios, and detailed uncertainty breakdowns—have established a robust foundation for future flux predictions at the DUNE ND 2×2 detector.

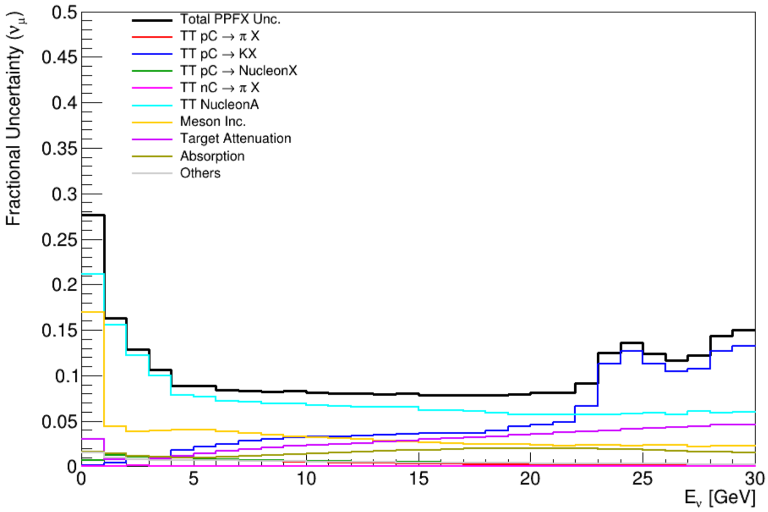

Figure 2: Fractional uncertainties of the PPFX-reweighted flux with dominant components. TT stands for thin target.

Upcoming work will incorporate newly published NA61/SHINE hadron production data (see Refs. [8, 9]), which provides direct measurements for proton–carbon interactions at 120 GeV/c—the same energy as the NuMI beam at Fermilab. This represents a major improvement over previous reliance on NA49 data at 158 GeV/c, which required momentum scaling and introduced additional systematic uncertainty due to the Feynman-x scaling procedure. The NA61/SHINE results include both charged and neutral hadrons, allowing for more precise and reliable flux predictions.

As part of my ongoing involvement in the DUNE collaboration, I plan to present these results at upcoming PPFX working group meeting. Additionally, I have been accepted to participate in the International Neutrino Summer School at Fermilab in August 2025, where I plan to present a poster on these results and discuss my work with the broader neutrino physics community..

3. Studies in Current Semester

- **FIZ/2/138: Experimental methods in particle physics.**
- **FIZ/2/003E: Beyond the standard model.**
- **Neutrino University, Fermilab Neutrino Physics Center Summer Lecture Series:**
- **Accepted to the International Neutrino Summer School 2025, Fermilab (August 11–22, 2025)**

4. Conferences and Workshops

- Following the PPFX Working Group meeting, participating in meetings and discussions as scheduled.
- Attended the DUNE Collaboration Meeting, May 19–23, 2025 (Fermilab, online).
- Planned presentation at the the PPFX Working Group meeting, July 2025 (date TBD).

- Planned poster presentation at the International Neutrino Summer School 2025, Fermilab, August 11–22.
- Attended Joint ND Prototypes + Sim/Reco Workshop, DUNE Collaboration Meeting, and LArSoft Workshop at CERN, January–February 2025.

References

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